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Fluorescent Clues to the Atmospheric Structure of Cool, Variable Stars

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Final Status Report (NAG 5-1777) covering 5/1/91 - 5/23/94.

Fluorescent Clues to the Atmospheric Structure of Cool, Variable Stars

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This NASA grant covers my research program, which involves the investigation of the relationship between Mg II *h* and *k* emission and fluorescent lines in variable, late-type giant stars. We have obtained LWP low and high dispersion observations for the semi-regular variable R Lyr and the Mira variable R Leo. IUE fluxes for Fe I (UV44) at 2823Å and 2844Å are combined with near simultaneous ground-based spectra of the Fe I (42) lines at 4202Å and 4308Å from McMath telescope on Kitt Peak. The Fe I (UV44) lines are seen as emission lines in almost all late-type variables, while the Fe I (42) lines are only seen as fluoresced emission features in the Mira variables. Mg II *h* and *k* are suspected to be *pumping* the Fe I fluorescent emission lines. These observations have enabled us to answer the following questions: Are the Mg II emission features caused by outward propagating shocks in both Miras and SRs? Why are the Fe I (UV44) lines fluoresced in both SRs and Miras, while the Fe I (42) lines only seem to be fluoresced in Miras? Does atmospheric structure differ in type or only in degree between the Mira-type and semi-regular variables?

1 Program Results:

This grant is associated with the 16th Year IUE observing program MIPDL, which is a continuation observing programs CVODL (15th Year of IUE), LGNDL (14th Year of IUE) and LGMDL (13th Year of IUE). Under these programs, we have taken 11 low-dispersion and 11 high-dispersion spectra of R Lyr, and 38 low-dispersion and 14 high-dispersion spectra of R Leo as shown in Table 1. Note that in addition to the LWP spectra tabulated below, one SWP-LO (SWP 49179) was taken for R Leo on 11/09/93 and 2 LWP-LO spectra (LWP 24686, 24687) were taken of an additional Mira-type variable, R Hya, on 1/08/93 for comparison to R Leo.

The analysis of the observations to date have led to some interesting discoveries concerning the fluorescent processes in these cool variable stars. Figures 1*a*, *b* demonstrate that the velocity fields in the Mg II emission feature formation depth are fundamentally different in the Mira stars as compared to the semi-regular variables. The dashed lines in these figures are the rest wavelengths of the Mg II lines in the frame of the stellar photosphere. The Mg II lines are approximately symmetrical to this reference point in the SRb while the Mg II lines are always blueshifted. Bookbinder, Brugel, & Brown (1989) have also noted this blueshift in spectra of the Mira star S Car and have suggested it results from a *Fermi-type* acceleration of photons across an outward moving shock which results in blueshifted photons. Figures 1*a*, *b* suggest, therefore, that the Mg II emission in the semi-regular variables may form in a nearly static 'chromosphere' and not an outward moving shock as is the case for the Miras.

Our NLTE radiative transfer calculations have demonstrated that the phase shift between the peak of the hydrogen Balmer line flux (at phase 0 = visual light at maximum) and the peak of the Mg II line flux (phase 0.2–0.4) directly results from the existence of a permanent chromosphere (called a *calorisphere* by some authors) that are shown to exist in non-dusty hydrodynamic models of pulsating variables (Bowen 1988). At phase 0, when the innermost shock is emerging from the photosphere, the optical depths of the Mg II lines is high enough for the inner 3 Å of the lines to form in this chromosphere. The underlying shock enhances the background flux below resulting in an absorption feature forming. As this shock propagates into the chromosphere, the background flux decreases such that Mg II goes into emission, with the peak emission occurring 0.3 in phase space past the visual flux maximum. Meanwhile the hydrogen Balmer lines do not have a high

Table 1: IUE Observations of R Leo Associated with this Grant

LWP Image	Date	Dispersion	Exp. Time	Program
19100	10/31/90	LO	20m 00s	LGMDL
19101		LO	75m 00s	
19514	01/07/91	LO	20m 00s	
19515		LO	105m 00s	
20044	04/01/91	HI	120m 00s	
20047		LO	13m 00s	
20048		LO	30m 00s	
20284	05/02/91	LO	60m 00s	
20288		HI	150m 00s	
20374	05/15/91	HI	85m 00s	
20375		LO	60m 00s	
20376		LO	20m 00s	
21679	11/09/91	LO	60m 00s	LGNDL
21680		LO	120m 00s	
22214	01/07/92	HI	110m 00s	
22215		LO	10m 00s	
22703	03/29/92	LO	10m 00s	
22704		LO	5m 00s	
22707		HI	120m 00s	
22708		HI	90m 00s	
22709		LO	30m 00s	
22710		LO	10m 00s	
22890	04/26/92	LO	8m 00s	
22894		HI	150m 00s	
22895		HI	90m 00s	
22896		HI	80m 00s	
24293	11/07/92	HI	90m 00s	CVODL
24296		LO	13m 00s	
24297		LO	45m 00s	
24684	01/08/93	HI	60m 00s	
24685		LO	5m 00s	
24688		HI	60m 00s	
25276	04/06/93	LO	60m 00s	
25280		HI	180m 00s	
25281		LO	30m 00s	
25282		LO	15m 00s	
25431	04/28/93	HI	180m 00s	
25432		LO	60m 00s	
25433		LO	20m 00s	
25434		LO	20m 00s	
25435		LO	30m 00s	

All exposure times are in minutes.

Table 1: IUE Observations of R Leo (continued)

LWP Image	Date	Dispersion	Exp. Time	Program
26709	11/09/93	LO	5m 00s	MIPDL
26710		LO	20m 00s	
26711		LO	105m 00s	
27192	01/08/94	LO	30m 00s	
27193		LO	120m 00s	
27802	04/02/94	LO	40m 00s	
27803		LO	125m 00s	
27910	04/15/94	LO	190m 00s	
28115	05/12/94	LO	55m 00s	
28116		LO	55m 00s	
28296	05/30/94	LO	60m 00s	
28297		LO	60m 00s	

All exposure times are in minutes.

Table 2: IUE Observations of R Lyr Associated with this Grant

LWP Image	Date	Dispersion	Exp. Time	Program
19097	10/31/90	HI	20m 00s	LGMDL
19098		HI	100m 00s	
19099		LO	10m 00s	
20045	04/01/91	HI	20m 00s	
20046		LO	2m 00s	
20285	05/02/91	HI	18m 00s	
20286		LO	5m 00s	
20377	05/15/91	HI	18m 00s	
20378		LO	5m 00s	
22705	03/29/92	HI	20m 00s	LGNDL
22706		LO	1m 30s	
22891	04/26/92	HI	20m 00s	
22892		LO	1m 30s	
22893		LO	8m 00s	
24294	11/07/92	HI	60m 00s	CVODL
24295		LO	1m 30s	
25277	04/06/93	LO	1m 30s	
25278		HI	20m 00s	
25279		HI	60m 00s	
25428	04/28/93	LO	1m 30s	
25429		HI	20m 00s	
25430		LO	10m 00s	

All exposure times are in minutes.

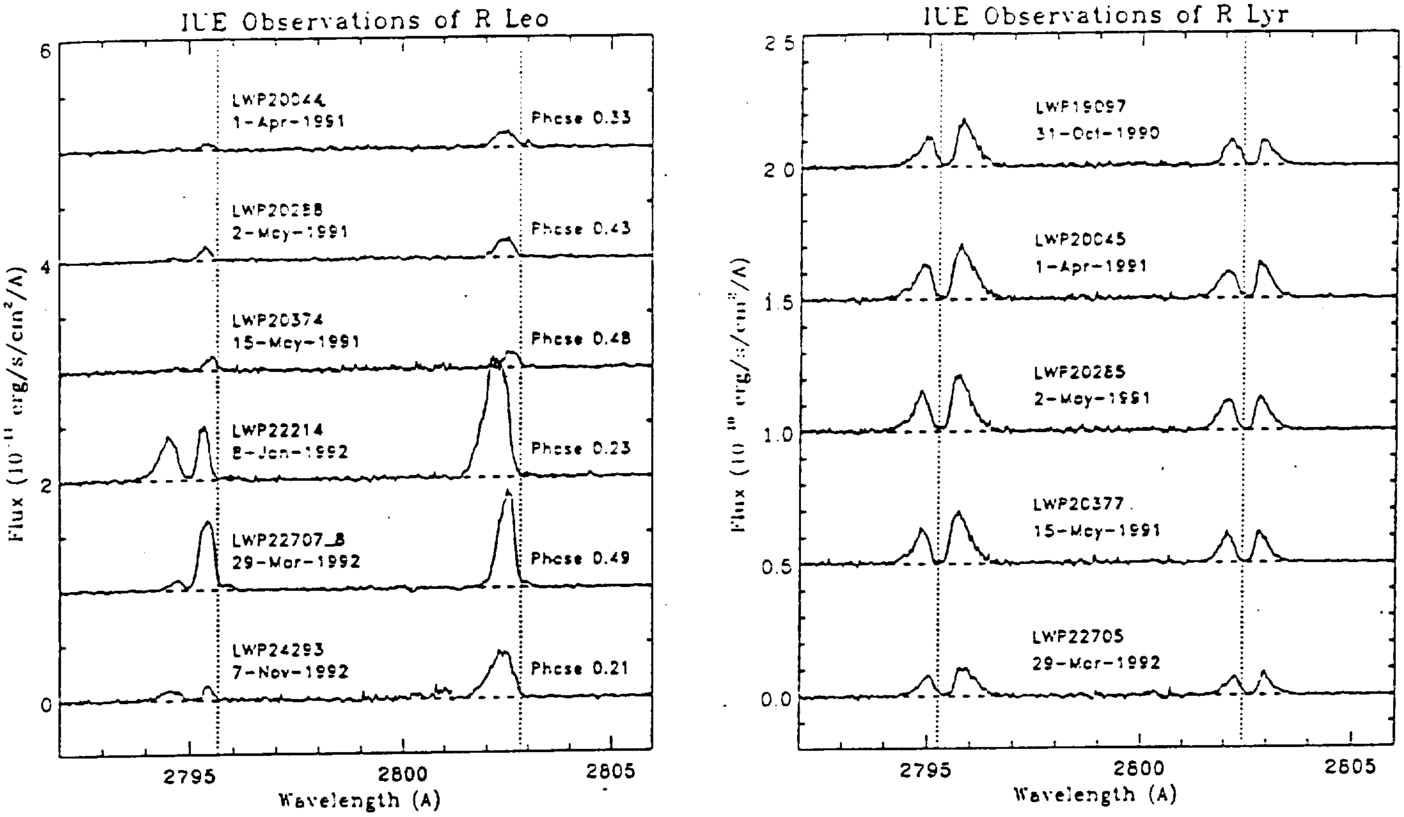

Figure 1: High dispersion IUE spectra of (*a*) the Mira variable R Leo and (*b*) the semi–regular variable R Lyr. The vertical dotted lines indicate the photospheric rest wavelength of the Mg II lines.

enough opacity to form in this chromosphere, and as a result, form in the innermost shock which results in their maximum flux occurring at phase 0. (Note that for calculations in hydrodynamic models where no permanent chromosphere exists, the peak flux of the Mg II and hydrogen Balmer lines are coincident at phase 0 since these features all form in the innermost shock.)

In the Mira variable, Fe I (UV44) emission peaks near phase 0, while the Fe I (42) emission peaks near phase 0.2–0.4 (see Figure 2). Since this maximum Fe I (UV44) flux occurs at the same phase as the hydrogen Balmer lines, it probably forms in the innermost shock. The Mg II line photons are plentiful in this shock at phase 0, but since the optical depth of these lines are exceedingly large ($\tau > 10^8$), the photons thermalize before making out of the atmosphere. However Fe I (UV44), with its nearly coincident line center wavelength with Mg II *k* and much lower optical depth, has no trouble emitting some of the Mg II photons from these depths through fluorescence. Meanwhile the Fe I (UV3) that is responsible for the Fe I (42) fluorescence, with its line center wavelength at 0.5 Å blueward of the Mg II *k*, must await Mg II emission line photons from the chromosphere to be emitted and hence lies above this Mg II emission depth. Hence for the Mira variables, the Fe I (UV44) fluoresceced lines are formed in the innermost shock while the Fe I (42) lines are formed in the cooler circumstellar environment.

We have not detected any variability in the Fe I (42) lines in R Lyr. Figure 3 shows the variation in the integrated Mg II flux from our non–overexposed high and low resolution images. The maximum variation in the Mg II flux is approximately 30% of the average flux level. Meanwhile Figure 4 ~~compares 2 McMath spectra in the 4202 Å region that~~ are nearly coincident with the minimum and maximum Mg II flux levels in Figure 3. As can be seen, the 30% variation in the Mg II flux has no effect on the Fe I (42) in this semi–regular variable. Comparisons made between

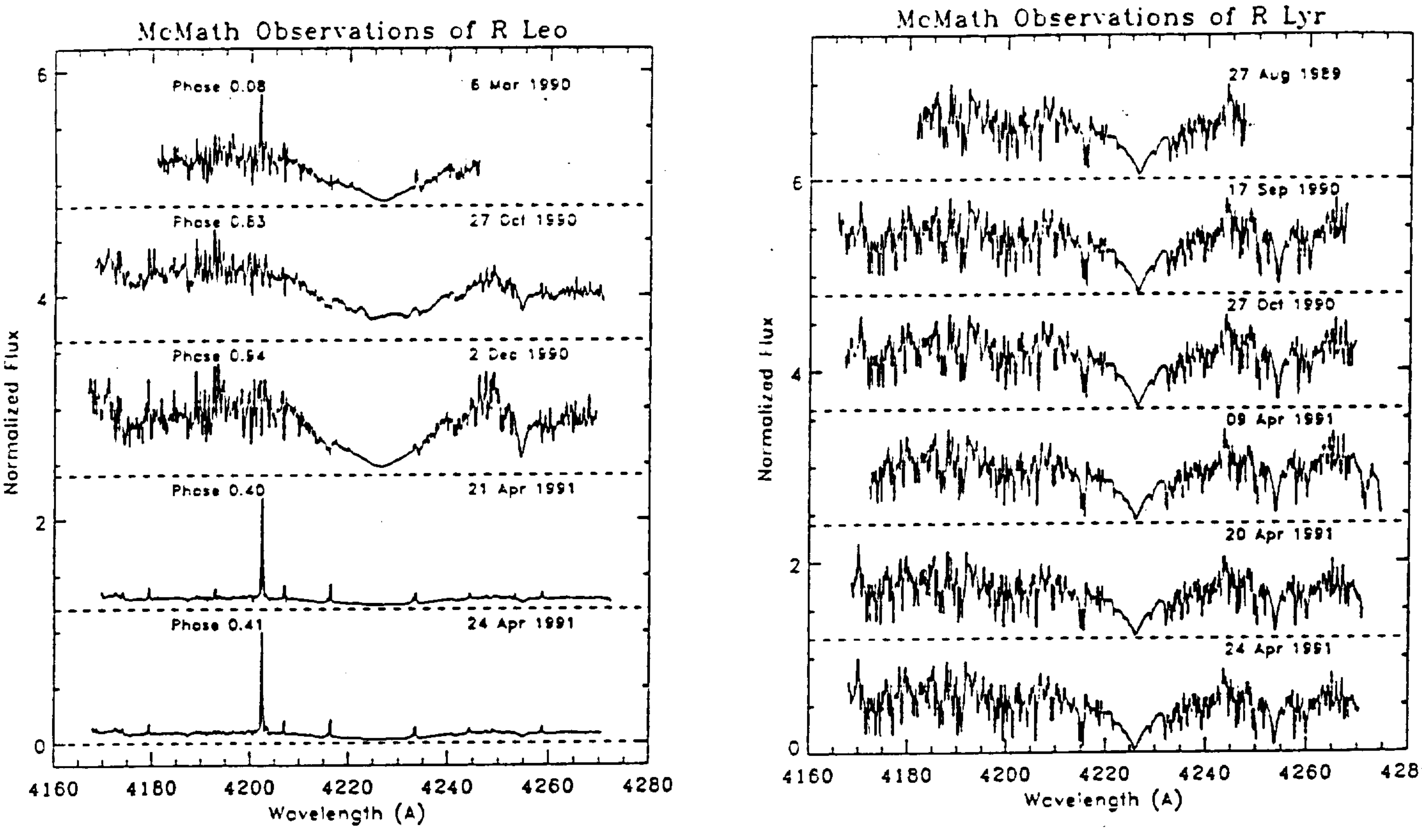

Figure 2: High resolution McMath spectra of (*a*) the Mira variable R Leo and (*b*) the semi–regular variable R Lyr. Note that these spectra represent a small sample of the ground–based observations we currently have on hand.

all of the McMath spectra obtained for R Lyr also show no variation in Fe I (42). Even though R Lyr has evidence for overlying absorption over the Mg II *k* line, the cool circumstellar region is not thick enough for a significant number of Mg II photons to escape through the Fe I (UV3)/Fe I (42) route.

Our past observations of these stars have enabled us to answer many of the questions presented in understanding the fluorescent mechanism of these stars. The observations of R Leo however have introduced a number of new questions. Figures 5*a*, *b* show the variations in visual magnitude deduced from the FES camera (calibrated by the visual magnitude and FES counts of the non–varying K star ξ Dra) and the integrated Mg II flux. Please note that the visual magnitude of this star is varying in a normal fashion for a Mira–type variable with no apparent abnormalities between the cycles in 1991 and 1992. However the Mg II integrated flux deviates wildly between the 1991 and 1992 cycles. Which cycle represents the normal Mg II flux variation in this star? Should the 1992 cycle (larger fluxes) be more characteristic of R Leo in the ultraviolet, does the low flux levels in 1991 indicate a dust formation episode in the outer atmosphere of this star, similar to that suggested for Mira–like variable L_2 Pup by Brugel, Willson, & Bowen (1993)? Unlike L_2 Pup however, no peculiarities are seen in the visual light variation during this episode. Should the 1991 cycle (smaller fluxes) be more characteristic, does the high flux levels of 1992 indicate some peculiar "strong" shock episode? Another intriguing observation is the Fe I (3) emission seen near phase 0.4 in April 1991 (Figure 6). These lines were not seen at this phase during 1990 (note that the 1992 observations at this phase were "clouded out."). These lines represent the strongest in this multiplet yet they do not all share the same J–value in the upper state, so they are not fluoresced.

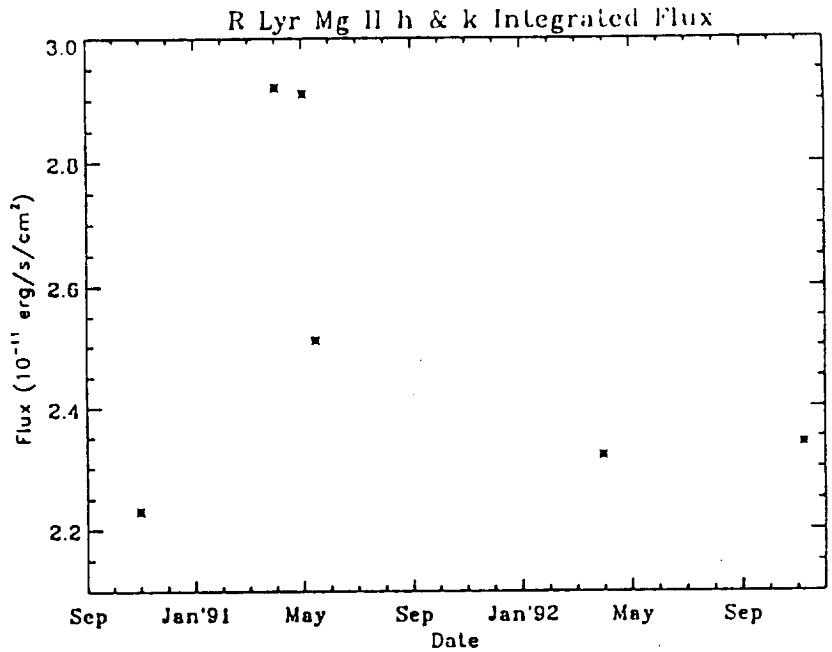

Figure 3: Variations in the Mg II integrated flux for the semi-regular variable R Lyr. Maximum variation is at the 30% level.

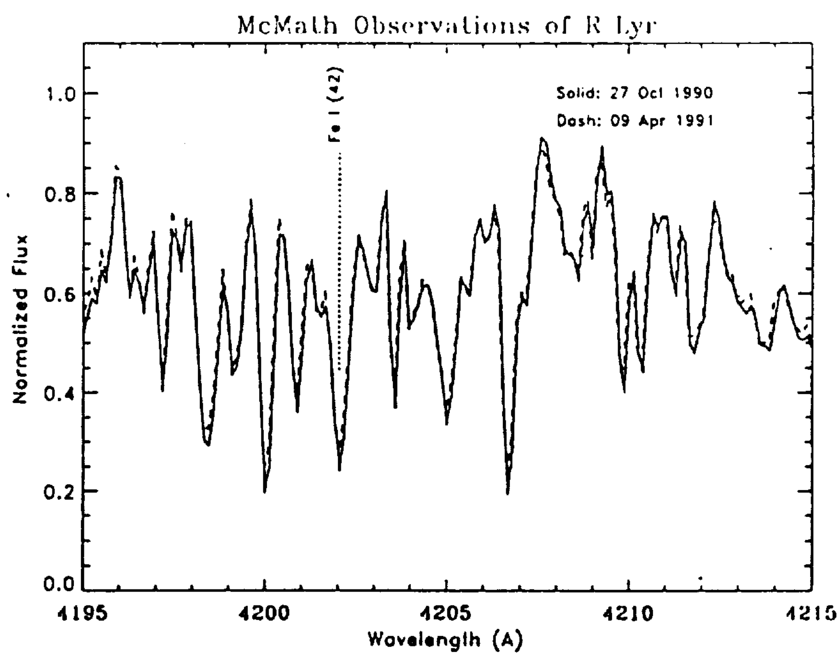

Figure 4: Comparison between two McMath spectra of R Lyr in the Fe I (42) spectral region. Note that no variation is seen in this Fe I between these two dates. The fact that the cores of the absorption lines in the dashed spectrum are slightly raised with respect to the solid spectrum is due to slightly different spectra resolutions (due to a slightly different field lens focus) between the two spectra.

These are spin–forbidden transitions and their appearance during the low Mg II flux cycle may indicate that this cycle is peculiar from a weak shock event (*i.e.*, a cooler shock will produce lower Mg II fluxes and perhaps be cool enough to excite the Fe I spin–forbidden lines.

Finally, we have submitted a paper to the Astronomical Journal entitled *Fluorescent Clues to the Atmospheric Shock Structure of Late–type Variable Stars.* This paper describes the observations and analysis of this long term monitoring program (*e.g.*, LGMDL, LGMDL, CVODL, and MIPDL) concerning the Mg II and Fe I fluorescent lines of late–type variable stars. We suspect that this paper will become the cornerstone in understanding the spectral characteristics of these stellar types.

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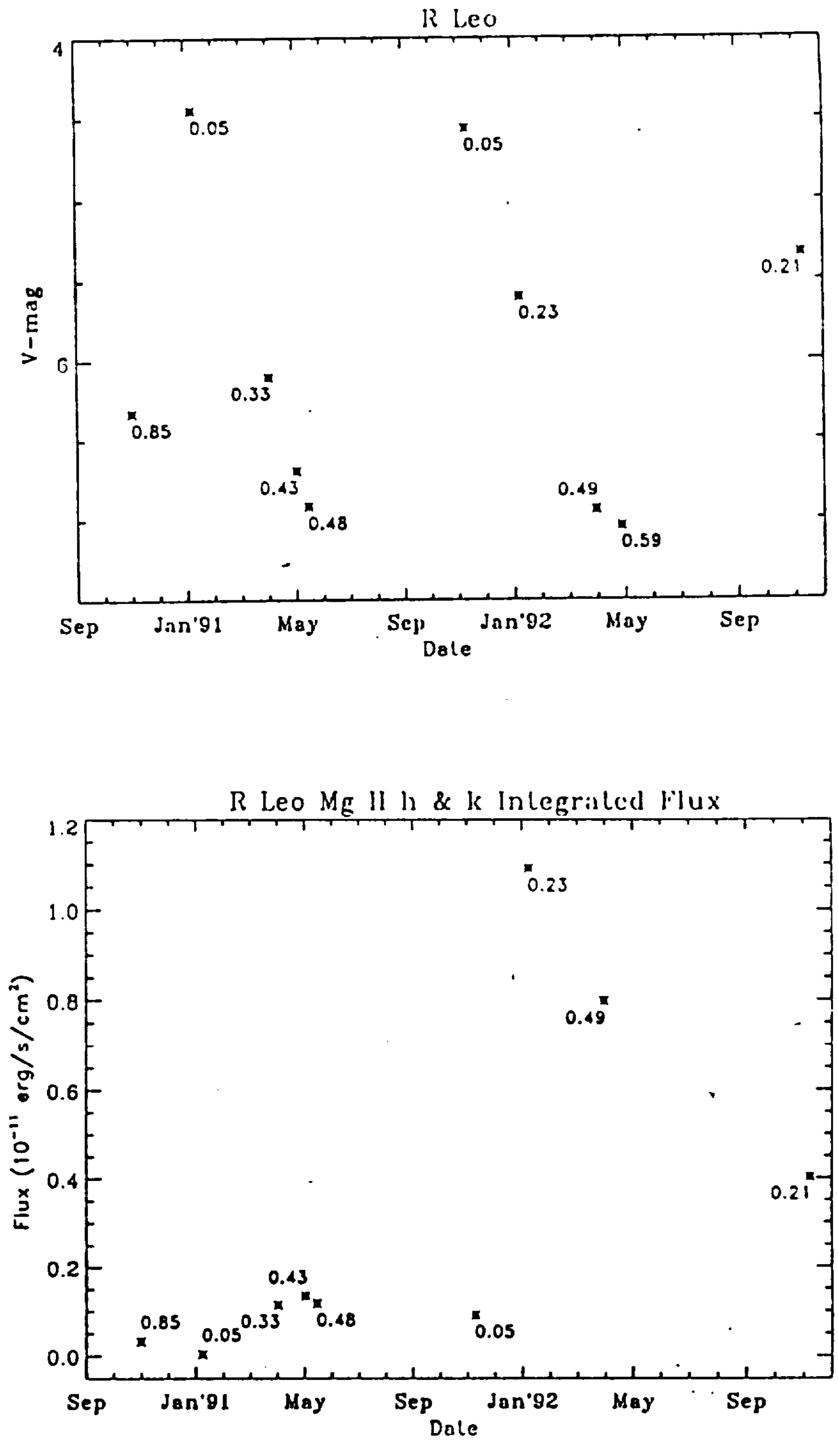

Figure 5: Variations in (*a*) the visual magnitude and in (*b*) the Mg II integrated flux of R Leo.

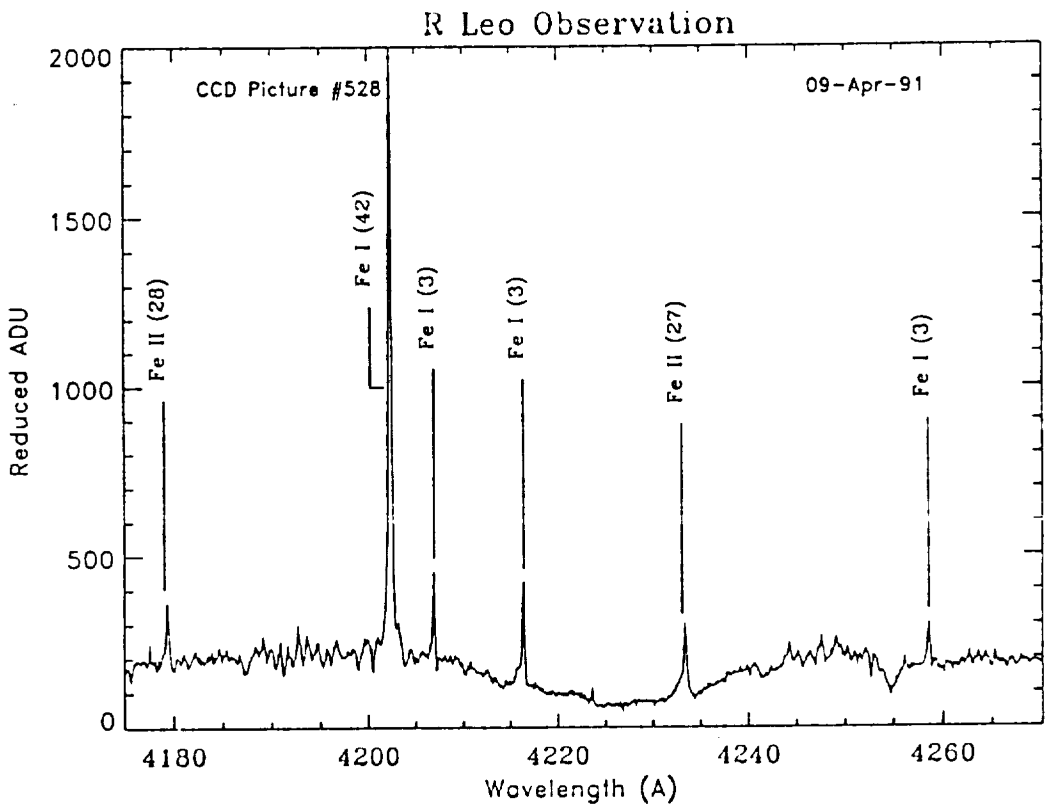

Figure 6: McMath spectrum of R Leo at phase 0.38. Note the Fe I (3) emission lines which were not detected during the previous cycle.